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A STUDY OF OPTICAL COLLIMATORS.(U)
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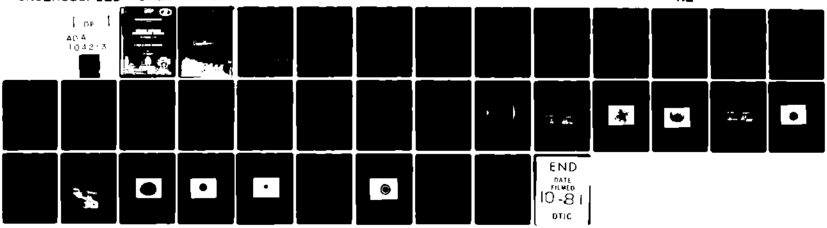

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A STUDY OF OPTICAL COLLIMATORS

by

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ABSTRACT

The operating principles of optical collimators are reviewed with special attention to the effect of filtering pinhole diameter, laser beamwidth and lens focal length on performance.

Three collimators were examined; a Jodon 50 millimeter beam expanding telescope; a Tropel 280-50 and a DREO design. Their ability to collimate a Spectra Physics Model 135 He-Ne laser beam was assessed.

RÉSUMÉ

On étudie les effets des principaux paramètres d'opération d'un collimateur optique sur ses performances. On s'attache principalement à l'influence du diamètre du filtre spatial, du diamètre du faisceau laser et de la longeur focale de la lentille.

Trois collimateurs furent examinés: un télescope Jodon de 50 millimètres, un Tropel 280-50 et un instrument construit au CRDO. On a évalué leurs performances à collimateur le faisceau d'un laser He-Ne Spectra Physics, modèle 135.

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A STUDY OF OPTICAL COLLIMATORS

1.0 INTRODUCTION

A collimator is basically a laser beam expander and spatial noise filter. It is composed of a microscope objective, a pinhole for noise filtering, and a collimating lens. Its output is generally assumed to be planar and uniform. However, in some instances, this assumption can not be made.

A requirement arose at DREO to use such a collimator to calibrate a photo-diode array detector with laser light. In such an application, the non-uniformity of the output of the collimator could not be ignored. The form of its intensity profile had to be measured and defined and the work reported in this technical note is an outcome of this requirement.

The output of an ideal collimator is a Gaussian beam, a noise-free expanded version of the input laser beam. Its intensity profile is determined by such design parameters as filtering pinhole diameter, input laser beam width, and the focal lengths of the two lenses in the collimator. In this report, the main principles of a collimator are established. Lens design is not dealt with. Instead, the discussion is restricted to determining the influence of each of the above design parameters on the performance of a collimator.

To gain further insight, three collimators were examined. Two of them: the Jodon 50 millimeter Beam Expanding Telescope and a laboratory model allowed for interchangeable pinholes and microscope objectives. The third, a Tropel 280-50 collimator, did not permit such flexibility.

These collimators were used to collimate a Spectra Physics Model 135 He-Ne laser beam. The results obtained were then compared to theory.

2.0 THEORY OF OPERATION

A collimator is a Keplerian telescope. A microscope objective focuses an input laser beam onto a pinhole. The pinhole filters noise from the beam and a collimating lens transforms the focused beam back into image space with a magnification factor. If the microscope objective and collimating lens are ideal aberration-free lenses, a collimator takes the form of the optical system depicted in Figure 1: two thin lenses separated by the sum of their focal lengths with a pinhole in the spatial-frequency plane between them.

2.1 Input Laser Beam

Laser beams expand as they propagate. Their phase fronts are slightly curved and their intensity profiles are not uniform. To maximize the performance of a collimator, its input must be derived from a TEM_{00} mode laser (1). Higher mode lasers produce beams whose intensity profiles vanish at one or more points. It is impossible to expand their outputs into uniform, collimated beams.

The majority of TEM_{00} lasers emit Gaussian spherical beams. These beams have the property that they shrink to a minimum diameter at a point, where their phase fronts are planar, called the beam waist. Furthermore, their intensity profiles remain Gaussian as they propagate outward from the beam waist. Kogelinik and Li (2) have demonstrated that, at a distance Z from the beam waist, the complex amplitude profile of a Gaussian spherical beam takes the form:

$$u(r) = \frac{u_0 W_0}{W(Z)} \exp \left\{ -r^2 \left[\frac{1}{W^2(Z)} + j \frac{\pi}{\lambda R(Z)} \right] \right\} \times \exp \left\{ j \left[\frac{2\pi}{\lambda} Z - \Phi(Z) \right] \right\} \qquad (1)$$

where

r = distance from the centre of the beam

u_0 = constant

W_0 = spot size of the beam at the beam waist

λ = wavelength of the laser

$W(Z)$ = spot size of the beam

$$= W_0 \left[1 + \left(\frac{\lambda Z}{\pi W_0^2} \right)^2 \right]^{\frac{1}{2}} \qquad (2)$$

$R(Z)$ = radius of phase front curvature

$$= Z \left[1 + \left(\frac{\pi W_0^2}{\lambda Z} \right)^2 \right] \qquad (3)$$

and

$$\Phi\ (Z) = \text{phase shift.}$$

Note that the spot size of a Gaussian spherical beam is the value of r at which the intensity profile of the beam

$$I(r) = \frac{u_0^2\ W_0^2}{W^2(Z)}\ \exp\left(\frac{-2r^2}{W^2(Z)}\right) \quad (4)$$

has fallen to e^{-2} its value on axis. See Figure 2.

Figure 3 depicts the outward expansion of a Gaussian spherical beam from the beam waist. Evidently, the spot size of the beam remains more or less constant at first. Some researchers (3) consider

$$Z_R = \frac{\pi W_0^2}{\lambda}, \quad (5)$$

the Rayleigh range, to be the upper bound of this collimated region. In any case, there is a direct trade-off between the extent of this collimated region and W_0, the minimum spot size of the beam.

At large distances from the beam waist, the beam becomes a spherical wave; its width diverges linearly with distance. Moreover, the smaller the beam, the more it diverges.

2.2 Filtering Pinhole Diameter

Multiple reflections from inside the laser, dust and the like will degrade a laser beam with high-frequency noise. To effectively remove this noise, the focused beam is passed through a pinhole whose diameter is small enough to block the high spatial-frequencies characteristic of the noise. The pinhole diameter must also be large enough to pass a substantial amount of the energy in the beam. If, for example, the diameter of the pinhole is three times the spot size of the focused beam, 99% of the energy will be transmitted. However, if the pinhole diameter is only two times the spot size, the percentage is reduced to 86.

Now, suppose that a TEM_{00} laser beam is incident on the input plane of the collimator in Figure 1. Suppose also that the input plane is at a distance Z_S along the optic axis from the beam waist of the beam and that W_S and R_S are the values of W(Z) and R(Z) respectively of the beam at Z_S. The

microscope objective focuses the input laser beam onto the filtering pinhole. Hence, referring to Goodman (4), the complex amplitude profile of the focused beam can be shown to be proportional to

$$u(r) = \frac{\pi W_0^2 u_0}{j \lambda f_M} \exp \left\{ \frac{-\pi^2 W_0^2 r^2}{\lambda^2 f_M^2} \right\} \times$$
$$\exp \left\{ j r^2 \frac{\pi}{\lambda f_M} \left[\frac{Z_S}{f_M} + 1 \right] \right\} . \tag{6}$$

The focused beam, consequently, has a Gaussian intensity profile. It has a spot size of

$$W_f = \frac{\lambda f_M}{\pi W_0} . \tag{7}$$

and a radius of curvature of

$$R_f = \frac{f_M^2}{Z_S + f_M} \tag{8}$$

This is provided, of course, that the effect of lens-edge diffraction can be neglected.

Collier, Burckhardt and Lin (1) recommend using a ten micron diameter pinhole when

$$\lambda = 0.6329 \text{ microns},$$

$$f_M = 16 \text{ millimeters},$$

and $$W_0 = 1 \text{ millimeter}.$$

More specifically, they recommend that D_p, the diameter of the pinhole, be on the order of three times W_f. Microscope objective power

$$PX = \frac{160}{f_M} \text{ millimeters} \tag{9}$$

so, in terms of PX,

$$D_p = \frac{480}{\pi W_0} \frac{\lambda}{PX} . \tag{10}$$

Note, W_0 is in millimeters.

The Spectra Physics Model 135 He-Ne laser produces a beam with a spot size of approximately half of a millimeter. In Table 1, possible pinhole-microscope objective power filtering combinations are listed for this laser. The pinhole diameters are those commonly found in collimators and spatial filters and all combinations satisfy equation (10).

TABLE I

Pinhole-Microscope Objective Power Filtering Combinations For A 0.5 Millimeter Spot Size He-Ne Laser Beam

Pinhole Diameter (microns)	Microscope Objective Power
5	38.7
8	24.2
10	19.3
25	7.7

2.3 Entrance Aperture

Up to now, we have neglected the effect of lens-edge diffraction. The input laser beam was assumed to be smaller than the entrance aperture of the microscope objective. When this is not the case, not only is the intensity of the focused beam reduced but its amplitude profile is no longer Gaussian. It is intermediate (5) between that of the Airy pattern of the truncating aperture and that of the untruncated focused beam. Therefore, the entrance aperture of a collimator should be at least three times the spot size of the laser beam it is designed to collimate.

2.4 Relative Focal Lengths

The collimating lens, in Figure 1, forms the Fourier transform of the filtered focused beam multiplied by a phase term in the output plane of the collimator. It can be shown that (4), in the noise-free case, the complex amplitude profile of the resulting collimated laser beam is proportional to

$$u(r) = \frac{-f_M}{f_L} \frac{u_0}{\sqrt{1 + K^2}} \exp \left\{ \frac{-f_M^{\,2}}{f_L^{\,2}} \frac{r^2}{W_0^{\,2}} \frac{(1 - jK)}{1 + K^2} \right\} \tag{11}$$

where

$$K = \frac{Z_S}{Z_R} + \frac{f_M}{Z_R} \left(1 + \frac{f_M}{f_L}\right) . \tag{12}$$

Note the pinhole is assumed here to have passed the focused beam unaltered.

The collimated beam is, therefore, just an expanded version of the original input laser beam at its beam waist times a phase term. It has a spot size of

$$W_1 = \frac{W_0 \, f_L}{f_M} \sqrt{1 + K^2} \tag{13}$$

and a radius of curvature of

$$R_1 = \frac{\pi}{\lambda} \frac{f_L^{\,2}}{f_M^{\,2}} W_0^{\,2} \left[\frac{1}{K} + K \right] . \tag{14}$$

Under normal working conditions, Z_R is much greater than Z_S and f_M.

Hence,

$$K \ll 1$$

and (13) and (14) simplify to

$$W_1 = \frac{f_L}{f_M} W_0 \tag{15}$$

and

$$R_i = \frac{\pi}{\lambda} \frac{f_L{}^2 \, W_0{}^2}{f_M{}^2} \frac{1}{K} \tag{16}$$

respectively. The magnification of a collimator is given by the ratio of the focal lengths of its two component lenses: f_L/f_M. Furthermore, in the back focal plane of the collimator, K can be shown to have decreased to a value of

$$\frac{Z_S}{Z_R} + \frac{f_M}{Z_R} \ . \tag{17}$$

The collimated beam is slightly convergent but not enough to be noticeable. A shearing interferogram of the beam should contain well ordered horizontal fringes.

To minimize noise due to internal reflections in the collimating lens and as an added filtering feature, the collimating lens in commercial collimators is enclosed in a tapered lens barrel. This is so that only the expanding, filtered, Gaussian spherical beam is collimated and that it is not truncated by the collimating lens.

3.0 EXPERIMENTAL RESULTS

The following sub-sections provide experimental results which were obtained using the three types of collimators.

3.1 Jodon 50 Millimeter Beam Expanding Telescope

The Jodon collimator, (see Figure 4), incorporates Jodon's LPSF-100 spatial-filter and a three element f/3.2 collimating lens. The device allows for completely adjustable and removable microscope objectives and pinholes. The pinholes, which are mounted on ring magnets, can be translated in both the x and y directions. They range in diameter from two microns to 100 microns. At DREO, there are a standard 25 micron pinhole, 10 micron, and a 5 micron pinhole.

The microscope objective are standard achromatic lenses. They are available in powers of 1 to 60 and can be translated along the Z axis for fine focusing. We have only two Jodon objectives: the 10x and 20x, but most

other available objectives fit the device.

According to Table I, to filter a 0.5 millimeter spot size He-Ne laser beam, one should use either a 5 micron pinhole with a 38.8 power microscope objective or a 10 micron pinhole with a 19.3 power objective. The closest to a 38.8 power objective is a 42 times objective and to a 19.3 power objective, a 20 times objective. In any case, either filtering combinations should produce clean, expanding, Gaussian spherical beams. In practice, this was not found to be the case with the LPSF-100 spatial filter. The 10 micron pinhole and 20 power objective produced the Fresnel zone pattern in Figure 5, namely, a central beam surrounded by higher order rings. Moreover, as one can see from Figure 6, the combination of 5 micron pinhole and 42 power objective yielded a filtered, expanding beam that was far from ideal.

There is evidence to indicate that the design of the spatial filter itself is the cause of its poor performance. The channel leading from the pinhole to the output in the device tends to restrict the expanding beam too much. This is especially true for the higher microscope objective powers.

Figures 5 and 6 were recorded on Polaroid Type 55 Black and White film at a distance of about seven centimeters from the spatial filter. A noise stop placed in front of the filter prevented light scattered off the pinhole holder from reaching the film plane.

The collimating lens has a focal length of 160 millimeters. This means that

$$\frac{f_L}{f_M} = \frac{160}{f_M} \text{ millimeters} \tag{18}$$

or, from equation (9),

$$\frac{f_L}{f_M} = PX. \tag{19}$$

The microscope objective determines the magnification of the device. Therefore, since the collimating lens has an output aperture of 55 millimeters, neither the 20x nor the 42x objective could expand the 0.5 millimeter spot size laser beam enough to fill the output aperture of the collimator. With the 20x objective, the collimated output beam was observed to contain a higher order ring. With the 42x objective, the beam contained a dark spot and a pronounced noise halo. The Jodon collimator is, obviously, designed to be used with larger laser beams than our 0.5 millimeter beam. The larger beams might not fill its output aperture completely but, at least, lower objective powers could be used.

3.2 Tropel 280-50 Collimator

Tropel 280 collimators are available in a variety of entrance-exit lens combinations. They are modular in construction and allow for interchangeable microscope objectives, collimating lenses, and filtering pinholes. Pinhole position can be adjusted to within 1.5 microns in both the x and y direction. There is also a fine axial focusing adjustment for the microscope objective and collimating lens.

The 280-50 Tropel collimator at DREO, (see Figure 7), has an entrance lens diameter of 1.5 millimeters, an exit lens diameter of 50 millimeters, and 8 micron pinhole. Both the microscope objective and the collimating lens are F/4 lenses.

Thus,

$$PX = 26.7,$$

$$f_L = 200 \text{ millimeters},$$

$$\frac{f_L}{f_M} = 33.3$$

and, for our 0.5 millimeter He-Ne laser beam,

$$W_i = 16.7 \text{ millimeters .}$$

Note that 26.7 is just slightly greater than the microsccpe power recommended in Table I for an eight micron pinhole. The filtered, expanding beam produced by the spatial filter in this collimator was found to contain a fairly clean Gaussian central beam with one faint higher order ring. Unfortunately, there was an obstruction suspended infront of the pinhole which could not be removed. It produced the artifact in the upper right hand corner of Figure 8.

The collimated output beam was visibly non-uniform. Samples taken across its center, (they are plotted in Figure 9), indicate it has a Gaussian intensity profile with a spot size of about 24.1 millimeters. There were also well defined diverging noise rings about the collimated beam but they posed no problem.

All of the intensity plots in this report were obtained with the help of a Coherent Radiation Power meter. The detector of this meter was mounted on a motor-driven unislide and samples were taken across the centre of the particular collimated beam with a one millimeter sampling aperture. The samples, normalized to their average value, were then plotted as a function of displacement from the leftmost edge of the beam.

3.3 DREO Collimator

The DREO collimator, shown in Figure 10, consists of a Data Optics spatial filter and a Tropel long focal length Fourier Transform lens. The spatial filter was modified to accept a series of seven pinholes mounted in two inch square aluminum sheets. The pinholes ranged in diameter from 2 microns to 200 microns but only three: the 5 micron, the 10 and 25 could be used in practice. They could be translated along all three orthogonal directions. The position of the microscope objective remained fixed.

The pinholes were only slightly recessed in their holders. This meant that, unlike in the spatial filters of the previous two collimators, the filtered expanding beam did not have to go through any output channel. As one can see from Figures 11 and 12, the resulting filtered beams were close to the ideal. It should be pointed out that the same microscope objectives were used in both the DREO and Jodon collimator. Any differences in the performances of their spatial filters can not, therefore, be accounted for by lens aberrations. However, the filtered expanding beams in this section and the next were recorded at a distance of 18 not 7 centimeters from the spatial filter. The noise stop, to be effective, had to be placed behind the spatial filter instead of infront of it as before.

The Tropel Fourier transform lens has a focal length of 621.8 millimeters and an output aperture of 60 millimeters. Consequently, one would need a 15.5 power objective to just fill the output aperture of the collimator with a 0.5 millimeter laser beam. The closest one could achieve to a 15.5 power objective, without exceeding that value, is a 10 power objective which according to equation 10, would necessitate using a 19.3 micron filtering pinhole. Instead, we filtered the beam with a 25 micron pinhole (see Figure 13). Further filtering was provided by a stop which allowed only the central order of the expanding filtered beam to enter the collimating lens.

Good agreement with theory was obtained with this filtering technique. A scan through the center of the resulting collimated beam showed its intensity profile to be Gaussian with a spot size of approximately 18 millimeters. (see Figure 14). The theoretical value of W_1 is 19.4 millimeters.

3.4 General Remarks on the Operation of a Collimator

A common technique to improve the performance of a collimator is to expand the input laser beam. The spot size of the resulting collimated beam is increased but one runs the risk of improper noise filtering of the laser beam. The pinhole might now be too large. Using a lower power objective will solve the filtering problem but it will also reduce the output spot size. Moreover, if the objective power is such that the pinhole truncates the focused beam, there will be some smoothing in the output beam at the expense of a less intense beam. For example, when using a 10 power - 10 micron pinhole filtering combination in the DREO collimator, the filtered expanding beam took the form of the Fresnel zone pattern in Figure 15. The spot size of the output beam was estimated to be 42 millimeters. Recall that, with no truncation, its theoretical value is 19.4 millimeters. Furthermore, we found that when the pinhole was replaced by a 5 micron pinhole, the spot size of the output beam increased to 60.5 millimeters but the beam was very faint. It is interesting to note that the filtering combinations: 10 micron - 20 power objective and 5 micron - 42 power objective, yield theoretical spot sizes of 38.8 millimeters and 81.5 respectively.

4.0 CONCLUSIONS

The output of a collimator is not a uniform plane wave but a collimated Gaussian beam. It has a spot size

$$W_1 = \frac{f_L}{f_M} W_0$$

where

f_L = focal length of the collimating lens

f_M = focal length of the microscope objective

W_0 = spot size of the laser beam at its beam waist.

The filtering pinhole in a collimator should have a diameter of the order of three times the spot size of the focused laser beam

or

$$D_p = \frac{480}{\pi W_0} \frac{\lambda}{PX} \text{ millimeters}$$

where

λ = wavelength of the laser,

PX = Power of the microscope objective.

The collimator, in other words, should be matched to the laser beam.

5.0 REFERENCES

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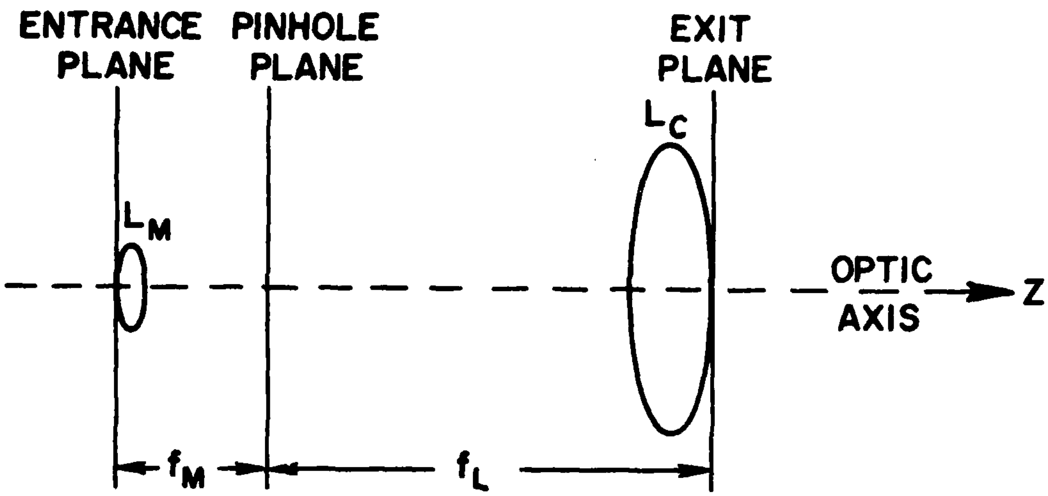


FIGURE 1 - A BASIC COLLIMATOR

L_M = microscope objective

L_C = collimating lens

f_M = focal length of microscope objective

f_L = focal length of collimating lens

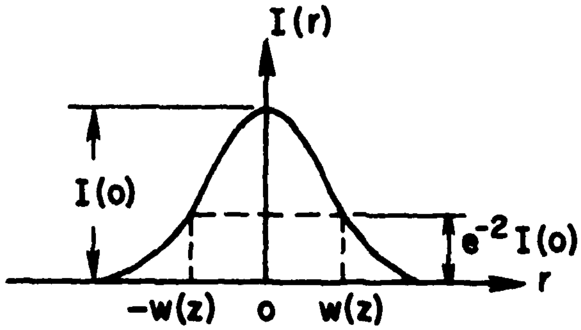


FIGURE 2 - INTENSITY PROFILE OF A GAUSSIAN SPHERICAL BEAM

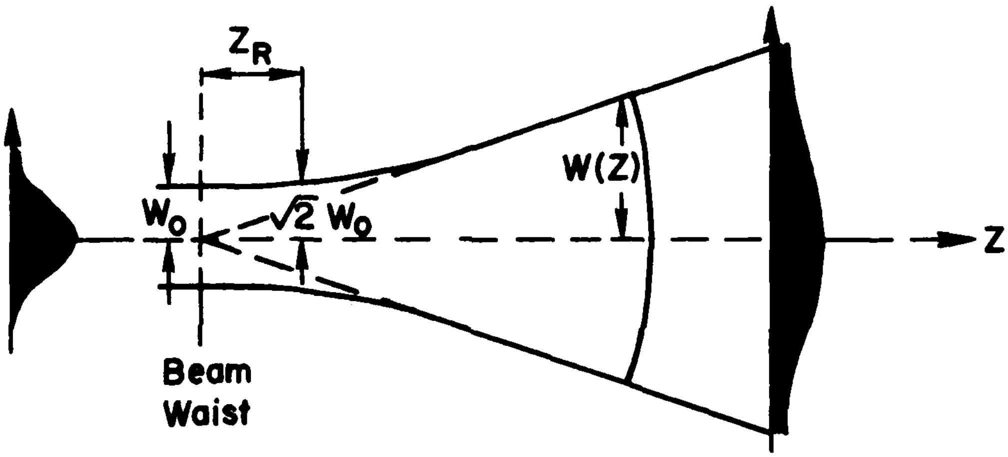


FIGURE 3 - OUTWARD EXPANSION OF A GAUSSIAN SPHERICAL BEAM FROM THE BEAM WAIST

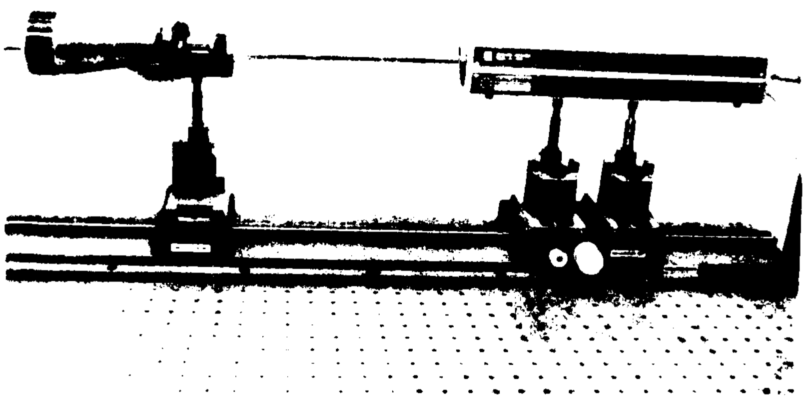


FIGURE 4 - JODON 50 MILLIMETER BEAM EXPANDING TELESCOPE AND A SPECTRA PHYSICS MODEL 135 HE-NE LASER

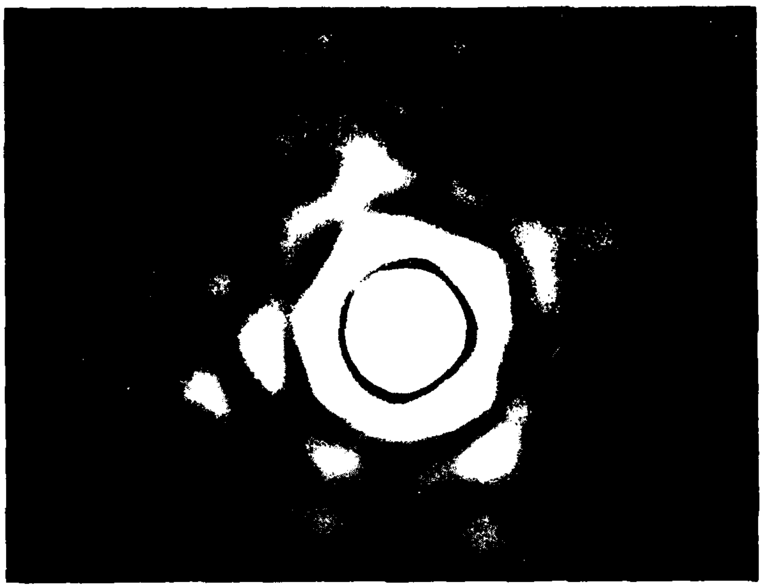


FIGURE 5 - OUTPUT OF LPSF-100 SPATIAL FILTER W_0 = 0.5 mm, λ = 0.6329 microns, D_p = 10 microns, PX = 20

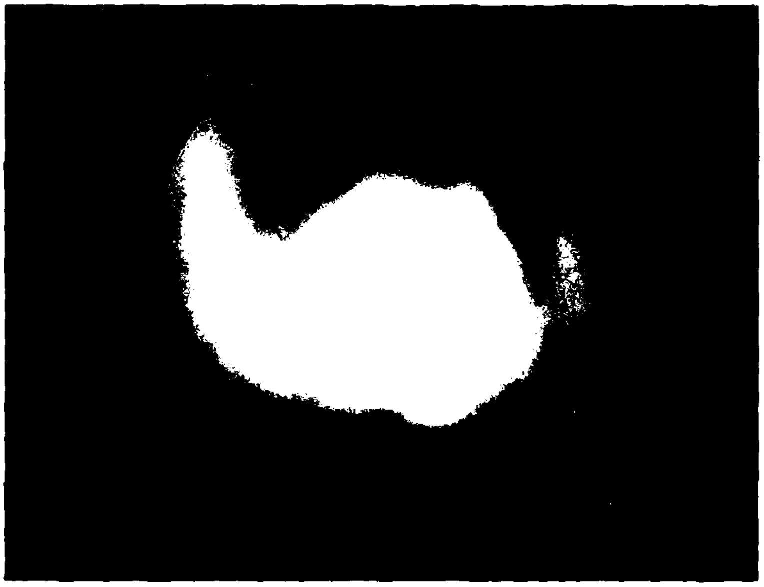


FIGURE 6 - OUTPUT OF LPSF-100 SPATIAL FITLER $W_0 = 0.5$ mm, $\lambda = 0.6329$ microns, D_p microns, FX = 42

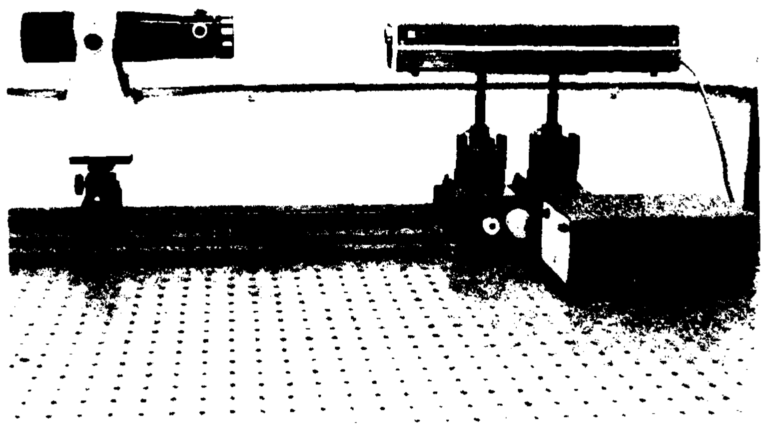


FIGURE 7 - A TROPEL 280-50 COLLIMATOR AND A SPECTRA PHYSICS MODEL 135 LASER

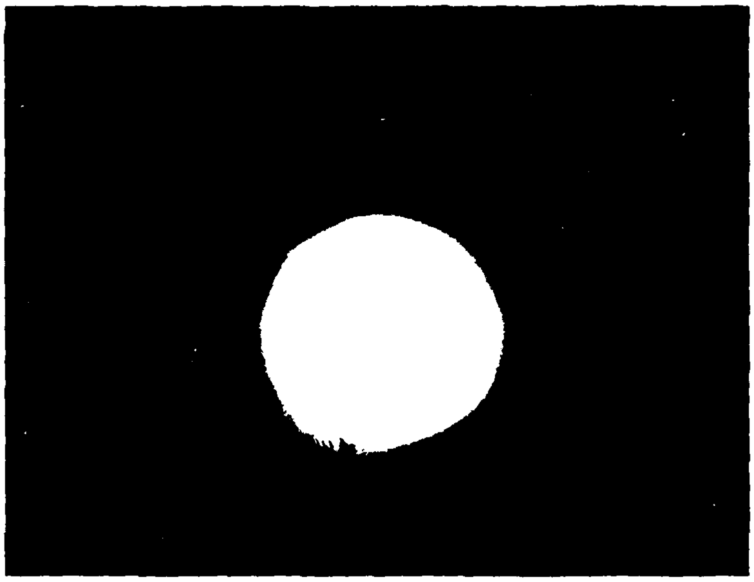


FIGURE [illegible] - OUTPUT OF SPATIAL FILTER IN
A TROPEL [illegible]80-6[illegible] COLLIMATOR

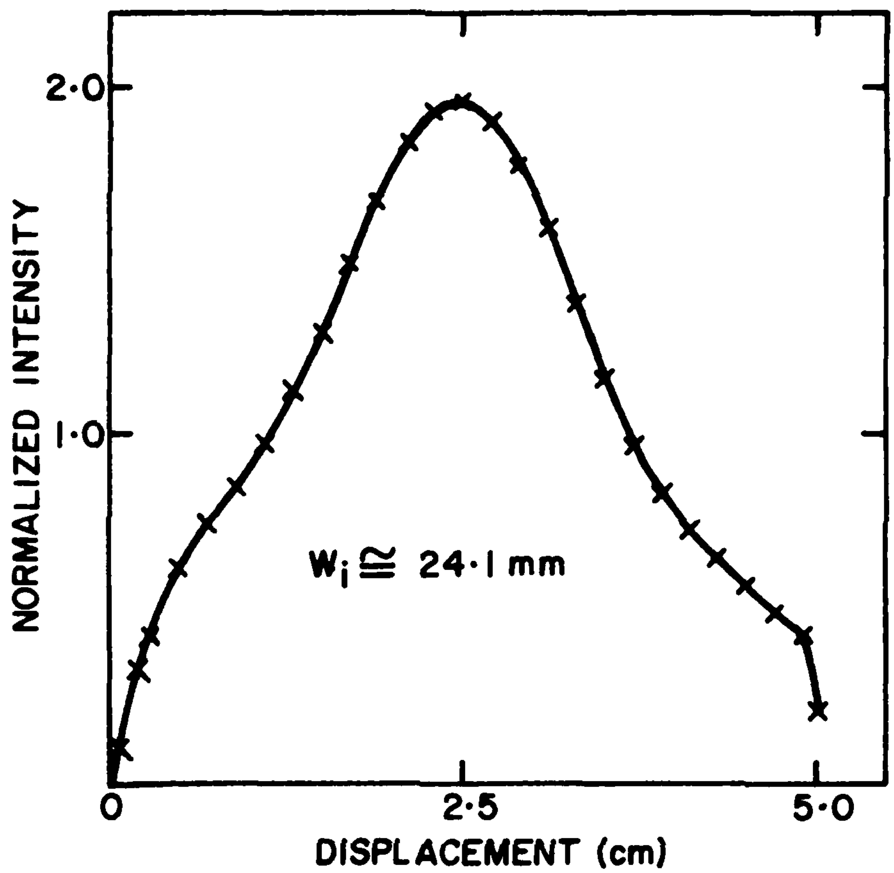


FIGURE 9 - INTENSITY VERSUS DISPLACEMENT-CENTER LINE SCAN OF TROPEL 280-50 COLLIMATOR OUTPUT $W_0 = 0.5$ mm, $\lambda = 0.6329$ microns

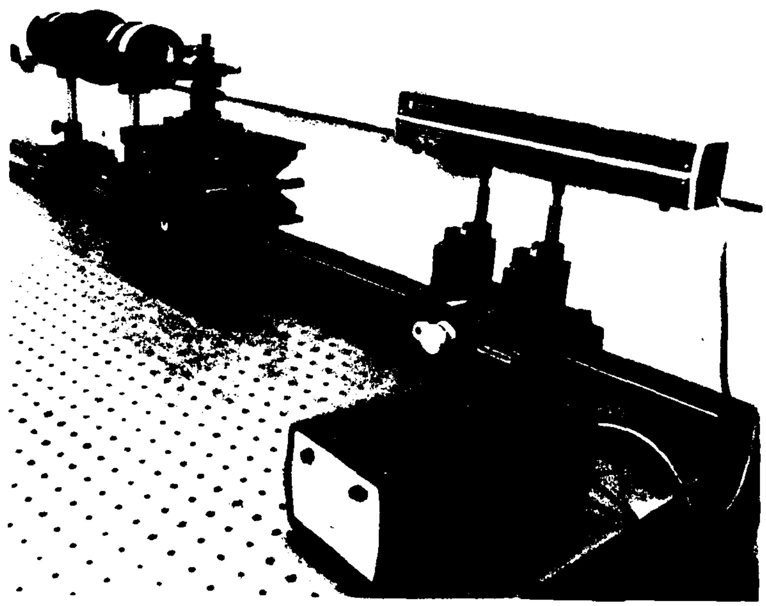


FIGURE 10 - DREO COLLIMATOR AND A SPECTRA PHYSICS MODEL 135 LASER

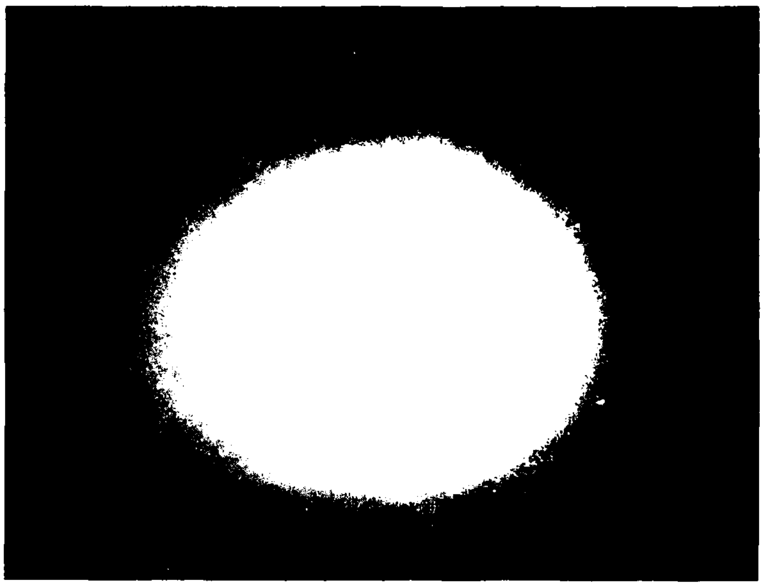


FIGURE 11 - MODIFIED DATA OPTICS SPATIAL FILTER OUTPUT
$W_0 = 0.5$ mm $PX = 42, D_p = 5$ microns
$\lambda = 0.6328$ microns

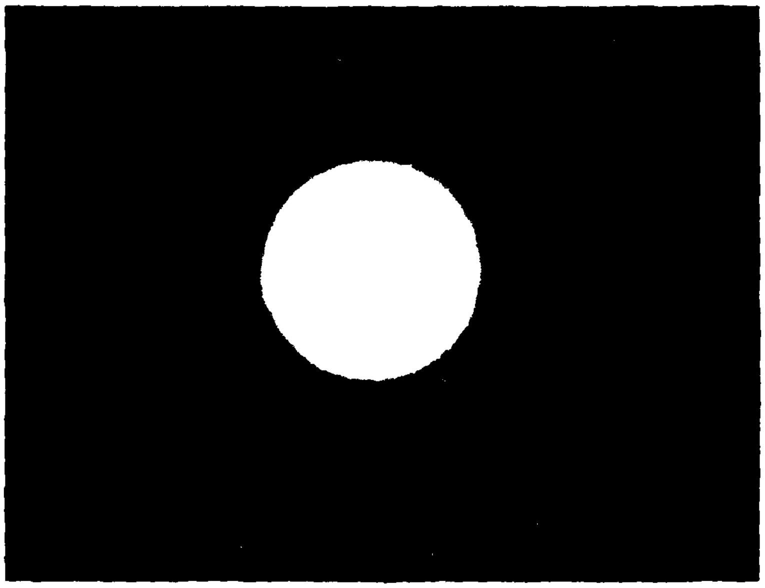


FIGURE 12 - MODIFIED DATA OPTICS SPATIAL FILTER OUTPUT
$W_0 = 0.5$ mm, $PX = 20$, $D_p = 10$ microns,
$\lambda = 0.6329$ microns

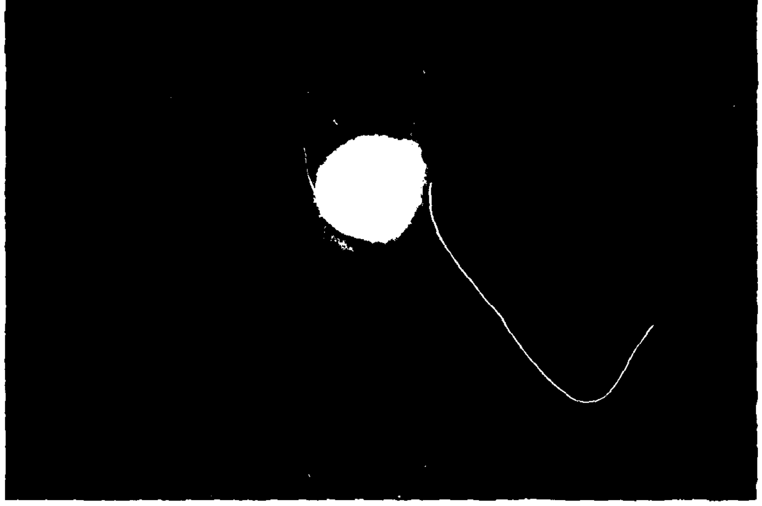


FIGURE 1? – [illegible]
W_0 [illegible] mm, [illegible],
λ [illegible] microns

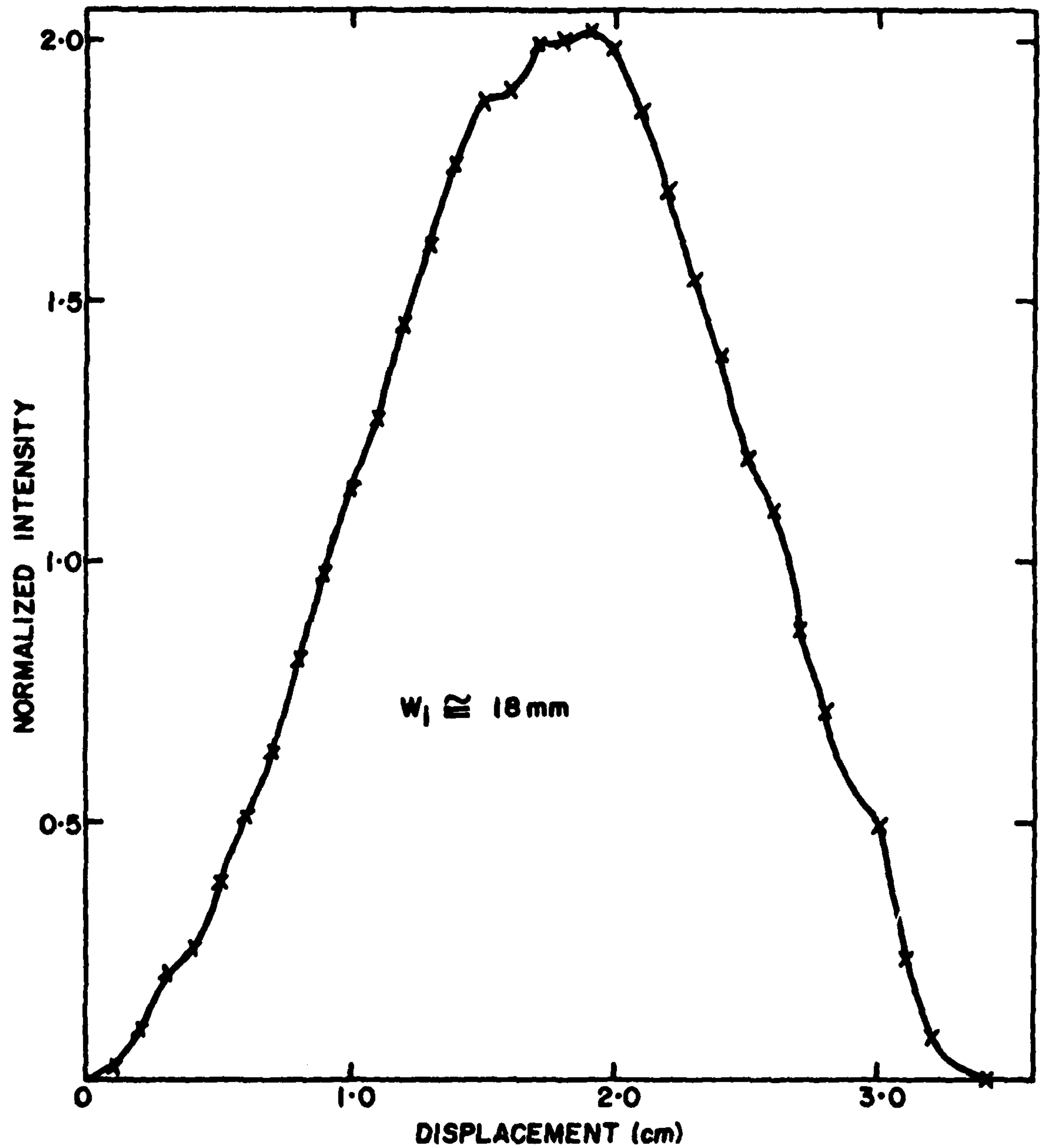
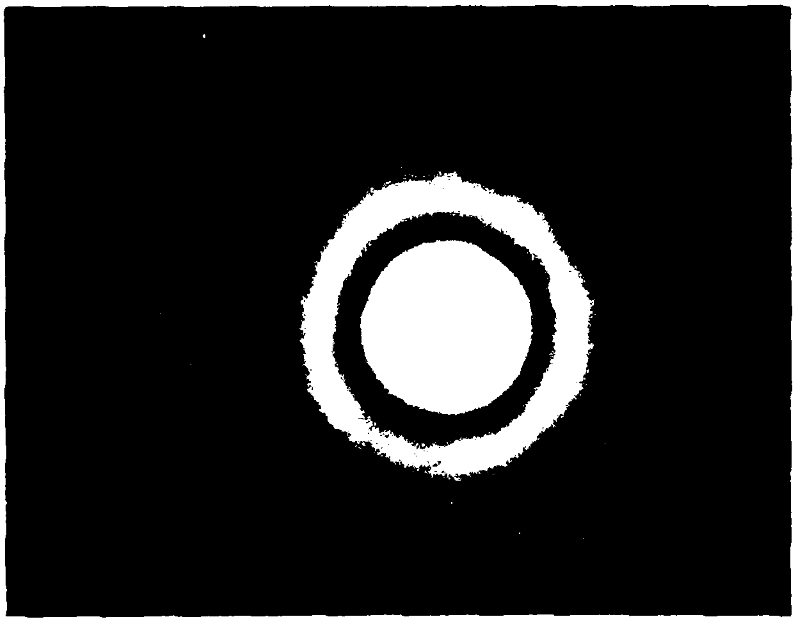


FIGURE 14 - INTENSITY VERSUS DISPLACEMENT-CENTER LINE SCAN OF HOMEMADE COLLIMATOR OUTPUT
D_p = 25 microns with stop, PX = 10
W_0 = 0.5 mm, λ = 0.6329 microns



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13. ABSTRACT

The operating principles of optical collimators are reviewed with special attention to the effect of filtering pinhole diameter, laser beamwidth and lens focal length on performance.

Three collimators were examined; a Jodon 50 millimeter beam expanding telescope; a Tropel 280-50 and a DREO design. Their ability to collimate a Spectra Physics Model 135 He-Ne Laser Beam was assessed.

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Security Classification

KEY WORDS

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PINHOLES

SPATIAL FILTERS

LASER

BEAM EXPANDING TELESCOPE

COLLIMATED LIGHT

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